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Characterizing variability and reducing uncertainty in estimates of solar land use energy intensity

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ABSTRACT

Estimates of the amount of land used for a defined amount of utility-scale electricity generation in the solar power industry, referred to here as *solar land use energy intensity* (LUEI), are important to decision makers for evaluating the environmental impact of energy technology choices. However, these estimates for solar LUEI are calculated using three difficult-to-compare metrics and vary by as much as 4 orders of magnitude (0.042–64 m^2/MWh) across the available literature. This study reduces, characterizes, and explicates the uncertainty in these values for photovoltaic (PV) and concentrated solar power (CSP) technologies through a harmonization process. In this harmonization process, a common metric is identified and data existing in other forms are converted to the metric, where possible; standard algorithms for calculating solar LUEI are developed; gaps and deficiencies in the literature calculations are identified and remedied; and differences among the resulting estimates are characterized and analyzed. The resulting range of harmonized solar LUEI estimates is reduced to 2 orders of magnitude [5–55 (m^2y)/MWh]. Due to variables such as technology and location, there is a significant amount of irreducible variability in general solar LUEI estimates. However, this variability does not necessarily represent uncertainty, as most of it can be explained by choices in calculation input parameters. This study finds that key solar technology- and location-dependent parameters such as insolation, packing factor, system efficiency, and capacity factor all vary widely across studies, and thus all share in the overall variability of solar LUEI. Only land use at the site of solar electricity generation facilities is considered because lifecycle land use beyond the site (for manufacturing, disposal, etc.) is not widely accounted for in the existing literature. This study provides a basis for moving forward with standardized and comparable solar land use studies and for filling gaps in lifecycle solar LUEI.

Contents

Abbreviations: CSP, Concentrating solar power; PV, Photovoltaic; LUEI, Land use energy intensity

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1. Introduction

Concerns about the potential environmental impacts of utility-scale solar energy technologies, including the amount of land used, can present a barrier to solar energy development. To inform decision making, it is necessary to compare the land areas required for solar energy development with the land needs of other energy technologies. To accomplish this comparison, the spatial intensity with which each technology generates electrical energy must be known. However, no single definitive source for land use energy intensity (LUEI) exists for solar energy. Current published studies on land use for solar electricity generation present a wide range of intensity values—covering 4 orders of magnitude—and use several different metrics of measurement. They use differing data, study boundaries, calculation methods, and assumptions about location and technology to arrive at divergent results.

This study explicates the differences among the existing solar energy LUEI estimates across both photovoltaic (PV) and concentrating solar power (CSP), or solar thermal, technologies and reconciles as many of them as possible through a harmonization process. Harmonization is a meta-analytical method for bringing divergent study results into closer agreement through the reduction of inconsistencies in data, calculations, and assumptions. The overall goal of harmonization is to develop a robust understanding of the variation in existing study results [1]. Because the amount of land used to produce a certain amount of electricity from solar power will always depend on variables such as location and technology, this study proposes two standard algorithms, or meta-models, for calculating solar LUEI. This study does not use harmonization to eliminate all variability in LUEI values. Instead, it intends to preserve the natural variability present among different technologies and locations while reducing error caused by inappropriate assumptions and inconsistent calculation techniques.

The analysis of land use in this study is limited to the site of the deployed solar energy technology. While the preponderance of existing literature on the subject only addresses onsite land use, several authors [2–6] have explored land use in other stages of the solar energy technology lifecycle, including land used for construction, material acquisition, and generation of the energy used in manufacturing. However, these sources do not always clearly communicate what lifecycle stages they account for, and when they do, the stages accounted for are not always consistent between studies. Due to the limited availability of upstream and downstream land use information and the inconsistency with which it is covered, this analysis concentrated on land use at the site of the power plant.

2. Methods

To examine the differences among solar LUEI estimates, first a comprehensive set of estimates was aggregated from the literature. Those estimates were examined for assumptions, study boundaries, and methods of calculation. Then, estimates gathered from the literature that failed to include adequate information for the harmonization process were screened from further study. Finally, in an iterative harmonization process, standard algorithms for calculating LUEI were developed and used, along with supporting information from the literature, to reduce and explicate discrepancies in the aggregated LUEI estimates.

2.1. Data aggregation

To identify data for aggregation, a literature review was conducted. Studies containing LUEI estimates and solar specifications such as rated capacity[1], energy output, site area, capacity factor[2], packing factor[3], insolation[4], PV cell efficiency[5], and system efficiency[6] were included in the review. Of 115 articles identified as potentially useful, 29 contained solar LUEI data useful for our study, and are thus included in this report.

The solar LUEI estimates gathered from these studies were aggregated according to their metric of measurement. All supporting information, including the specific technology modeled, calculation method for the estimate, data or specifications used to make the calculation, boundaries of analysis, sources, and date of study, was also collected.

2.2. Screening

Unfortunately, many of the sources identified by the literature review fail to include any calculations or data to support the solar LUEI values they provide. Absent information that can be used to compare and contrast one calculation with another, or identify gaps in calculation methodology, these LUEI values cannot be harmonized (see Section 2.3 for information on this process). For example, estimates of insolation and capacity factor are highly dependent on the specific solar technology being used and its location. Both of these factors affect the calculated LUEI. If these (and other) assumptions are not communicated, it is not possible to determine the reason for differences among LUEI estimates.

[1] Capacity is the electrical load that a plant is rated to be able to supply (the maximum power output) [7].

[2] Capacity factor is ratio of a plant's average power output over a specified period of time (normally a year for the solar industry) to its rated capacity [7].

[3] Packing factor is the ratio of a plant's solar collector array area (the area actually covered by the PV panels or CSP mirrors) to the total land area occupied by the array [7]. This includes land area left open to avoid shading and to allow access for maintenance [2].

[4] Insolation is the solar power density incident on a surface [7]. This varies by location due to differences in latitude and climate.

[5] PV cell efficiency is the ratio of electrical energy produced by the cell to the solar energy incident on the cell [7].

[6] System efficiency is the ratio of the energy produced by the power plant to the solar energy incident on the solar collectors [7].

Furthermore, lacking this information, it is not possible to determine whether an extreme or errant assumption (or failing to include a key factor in the calculation) is responsible for an outlying LUEI estimate. Studies lacking the necessary information for harmonization were eliminated from this analysis.

2.3. Harmonization

Harmonization is a meta-analytical method for bringing divergent study results into closer agreement through the reduction of inconsistencies in data, calculations, and assumptions. This process can take different forms, but the primary goal is to determine the "legitimate variation" among the study results [1]. In the case of solar LUEI, this variation is due to differences in realistic technology and location assumptions. Excess variation might be due to flawed calculations, missing data, differing system boundaries, or questionable factor values. Other goals of harmonization include identifying gaps in the analysis or the knowledge base and constructing meta-models to standardize or improve future calculation of the metric in question. Harmonization meta-analyses have been previously performed in the energy and environmental impacts research area [8–10] but not specifically concerning land use for solar power.

Part of this harmonization consisted of converting all the LUEI values into a single metric so that they could be easily compared. The reviewed studies present LUEI estimates measured in three different metrics: square meters per megawatt (m^2/MW), square meters per megawatt-hour (m^2/MWh), and square meter-years per megawatt-hour [(m^2y)/MWh]. Respectively, they measure land used per capacity of the plant, land used per plant electricity output (presumably over the lifetime of the plant), and land used per annual plant electricity output. These metrics are not directly comparable. However, conversions can be made across them given certain assumptions. Because the last metric, (m^2y)/MWh, accounts for actual energy production and normalizes for different plant lifetimes, it was the chosen metric for comparison across sources. More information on the metrics and conversion calculations between them can be found in Section 3.2 and Section 3.4, respectively.

While converting the solar LUEI data into a single metric, discrepancies in assumptions and calculation methods across the different estimates of LUEI were simultaneously identified. For sources providing LUEI estimates directly, the calculation methods generally were inferred and then recreated from the presented estimates and data. For example, in addition to providing LUEI estimates, Fthenakis and Kim [2] provide insolation estimates for different cases and specifications on system efficiency, packing factor, and plant lifetime. Using a basic knowledge of solar electricity generation, it was possible to determine how these four factors would be combined to calculate LUEI. The calculation method was then tested to see if the result equaled the result reported in the study. This examination revealed that most studies use some variation on either of two general algorithms for solar LUEI calculation. These algorithms served as meta-models for examination of the studies for uncommon calculations and missing input parameters. Other parameters used for analyzing differences in the study estimates include the date of study publication (to account for technological advancement) and the specific solar technology studied.

Using these algorithms and parameters, gaps in some studies' calculations were filled and deficiencies in assumptions were identified. Filling gaps among parameters was necessary to convert some of the LUEI values to a common metric. The legitimate range of input parameters was characterized (e.g., differences in insolation values due to location). Harmonized solar LUEI estimates were then organized by the specific PV or CSP technology subcategory they described. For PV, the technology subcategories used were general, fixed tilt, one-axis tracking, two-axis tracking, and concentrating. For CSP, they were general, power tower, parabolic trough, dish/engine, and chimney. The general categories included sources where the specific technology was not identified and could not be determined. Finally, the resultant range of LUEI estimates was displayed across PV and CSP technology subcategories. The variability in key algorithm parameters was used to explain the magnitude of the resulting range in estimates.

3. Theory and calculation

The specific metrics evaluated and the algorithms developed from the harmonization process introduced in the methods section are discussed here in detail.

3.1. Screening

Screening for appropriate sources is a necessary step in any successful harmonization [1,10]. For harmonizations with many potential sources, screening can be strict enough to ensure only the highest quality data are included. For example, a recent meta-analysis on greenhouse gas emissions from CSP technologies by Heath and Burkhardt [10] eliminated all but 13 reference studies from an initial pool of 125. Criteria for screening can range from the completeness of reporting inputs and results in a study to that study's page length [1].

The pool of source studies on solar LUEI was smaller and broader in focus (covering both PV and CSP technologies) than that of Heath and Burkhardt [10], and therefore could not be as selective. The only screening criteria used for this study was the presence of supporting calculations or inputs for determining solar LUEI at the site of a utility-scale power plant. LUEI estimates lacking this information would have no basis for comparison with estimates from other studies during harmonization. This screening process eliminated all estimates from 13 out of the 29 studies whose data were initially aggregated [3,4,11–21]. Most of the data from the remaining 16 studies [2,5,6,22–34] continued in the harmonization process. Many of these studies contained multiple LUEI estimates. The screening process eliminated some, but not all, of the LUEI estimates from three of these studies [6,29,30]. The excluded data is reported in full in the online Supplementary materials.

3.2. Metric theory

Since the amount of land used by an electricity generation facility scales with the amount of electricity produced, land use data must be normalized for the output of the facility to be meaningful for generalization and comparison. Three different metrics are used in the literature: m^2/MW, m^2/MWh, and (m^2y)/MWh. None is directly comparable to any other without further calculation.

Because the megawatt is a unit of power, not energy, studies that report the m^2/MW metric rely on the plants' rated power capacities rather than their actual electrical output. Without knowing the percentage of maximum plant output capacity actually produced over the course of a year (the capacity factor), it is impossible to determine how much electricity the plant actually produces. In the absence of a known capacity factor, land use is normalized by dividing area by capacity in megawatts, resulting in the unit m^2/MW. Because this metric does not contain plant performance data, it should only be used to compare similar technologies implemented in similar environments, which lessens

its value as a tool of comparison among technologies. Nonetheless, 8 of the 28 studies reviewed in this project depend on this metric for their primary results for at least one solar technology [14,17–19,22,26,29,30].

Rather than relying on a plant's power capacity, the m^2/MWh metric uses its energy output. This metric divides the land area of the plant by its total lifetime electrical output. It communicates a straightforward value for the amount of land required for a unit of energy to be produced, and thus accounts for differences in plant operating conditions and assumptions. However, a limitation of this metric is that it fails to account for the time value of land use; it normalizes over plant lifetime but does not define that lifetime. For example, consider two PV power plants, A and B. A covers half the area of B (thus has roughly half the power capacity of B) and has twice the lifetime of B. Both plants produce the same amount of energy in their respective lifetimes. In this scenario, A would have an area/energy metric (e.g., m^2/MWh) equal to half that of B, simply because it uses half the land to produce the same amount of energy. But this is misleading, because A operates for twice as long as B does. The metric makes A look twice as efficient as B, but A merely exchanges area for time. This confusion can be avoided by using the metric for comparisons only between plants of equal lifetimes.

The (m^2y)/MWh metric improves upon m^2/MWh by annualizing electrical output. This annualization accounts for the time value of land use, thus allowing comparison of plants with different lifetimes. By including a time unit in the numerator, the metric normalizes for different plant lifetimes. Because it accounts for the time value of land use, and because it incorporates the actual energy output of a plant, this metric is the best suited for comparing across different solar technologies and locations. However, both the plant lifetime and the actual yearly electrical energy output of every plant being compared must be known (or assumed) for the metric to be calculated.

3.3. Meta-model algorithms

Upon examination of the aggregated study data, it was determined that most studies use some variation on either of two general algorithms for solar LUEI calculation. In their capacity as meta-models for the calculation of solar LUEI, these algorithms are both a result of the harmonization and an integral part of the analysis and calculation that occurs during harmonization. This only makes sense if harmonization is understood to be an iterative process. The algorithms emerged from analysis of calculation methods within the harmonization process and were then used to identify and complete gaps in other calculations during harmonization. Information gleaned from those other calculations then informed the design of the algorithm, and so on.

The first algorithm calculates LUEI from the average incident solar radiation—or insolation—of the plant's location (I)—measured in MWh/(m^2y), the efficiency of the solar technology in converting sunlight to electrical energy (E)—which is unitless, and the unoccupied land between modules of solar technology (which are spaced to minimize or optimize self-shading and allow for maintenance). The variable that represents the spacing between modules is the packing factor (P), which is unitless. In this study, this algorithm is referred to as the insolation method, and is given by Eq. (1).

$$\mathrm{LUEI} = \frac{1}{I \times E} \times P \tag{1}$$

The second algorithm, the area-output method, calculates LUEI from the plant or collector area (A)—measured in m^2—and the annual plant electrical output (O)—measured in MWh/y. It is given in Eq. (2). When output is not given, it can be calculated using the plant capacity (C)—measured in MW—and either the plant capacity factor (F_C)—which is unitless—or the annual full load hours (L)—measured in h/y, as shown in Eqs. (3) and (4).

$$\mathrm{LUEI} = \frac{A}{O} \tag{2}$$

$$O = C \times 8760(h/y) \times F_C \tag{3}$$

$$O = C \times L \tag{4}$$

Several of the sources that provide solar LUEI for this study cannot be fit to either of these algorithms. Most of these sources [23,32–34] provide ranges of land use based on model outputs from the National Renewable Energy Laboratory's System Advisor Model [35] or PVWatts tool [36] rather than performing simple calculations that can be inferred from the data provided. Broesamle et al. [31] use their own model to calculate solar production potential in Northern Africa using a cloud index, land cover data, and other factors. However, these sources are not precluded from this harmonization since all five provided at least some information on model inputs and assumptions that can be used for comparison with other studies.

3.4. Metric conversion

Since (m^2y)/MWh is the chosen metric for harmonization in this study, data using one of the other two metrics had to be converted. Conversion of m^2/MWh to (m^2y)/MWh is accomplished by multiplying by the plant lifetime. When the plant lifetime is not known, the standard lifetime of 30 years, which is used in most studies, was assumed. In addition to multiplying by the plant lifetime, conversion between m^2/MW and (m^2y)/MWh requires dividing by the product of the number of hours in a year (approximately 8760) and the capacity factor of the plant. This conversion is somewhat more problematic than the former because capacity factors were not often included in studies using the m^2/MW metric and therefore have to be assumed. Capacity factors are highly dependent on site characteristics and technology specifics.

Solar land use intensities given as m^2/MW and not accompanied by their own capacity factors were converted to (m^2y)/MWh using the capacity factors shown in Table 1. The selection of these capacity factors is based on an assumption of a U.S. location. The capacity factors for CSP technologies were given typical values for the U.S. Southwest. PV technologies were assigned a U.S.—average capacity factor. It should be noted that the estimate for dish engines is older—from 1997—and could be low.

Capacity factors consistent with the U.S. Southwest were used for CSP because almost all existing and planned CSP projects in

Table 1
Capacity factors for solar technologies.

Technology	Capacity factor
Parabolic trough without storage	0.25[a]
Parabolic trough with storage	0.40[a]
PV	0.18[a]
Dish engine	0.25[b]

This table shows the assumed capacity factors used for metric conversions when no capacity factor was listed in the source.

[a] [37].
[b] [38].

the United States are in the Southwest [33,39]. CSP technologies require direct, rather than diffuse, solar irradiance, and thus only function well in areas that tend not to be cloudy. PV technology, however, functions well in both direct and diffuse light. For this reason, PV plants are being installed in many regions of the United States. This study reflects the broader applicability of PV by using a PV capacity factor that is an average for the United States. While it is true that most large PV installations are planned for the Southwest, where total insolation is higher than other regions, over a quarter of existing U.S. utility-scale PV installations are in other regions [39], and a large amount of continued installation is expected along the eastern seaboard and parts of the Midwest over the next 40 years [33]. Nonetheless, the selection of a capacity factor for PV technologies has no impact on the final results of this study because no LUEI estimate for PV that was missing a capacity factor survived the initial screening process described in Section 3.1.

3.5. Filling gaps and identifying deficiencies

Comparing the algorithms described in Section 3.3 to available calculation parameters and methods revealed gaps in several of the studies' calculation methods. It was necessary to address these gaps in order to perform the metric conversion described in Section 3.4. Several were missing necessary capacity factors [22,26,29], while one lacked a packing factor [28] and another an insolation value [29]. These gaps were filled using accepted standard values. Capacity factors were taken from U.S. averages for different technologies published by the Department of Energy [37] and are displayed in Table 1. Insolation values for DeMeo and Galdo [29] were taken from Fthenakis and Kim [2] because they are average values (rather than values specific to a site—as are many of the insolation values given in the literature) and are typical for the data gathered in this study; 1800 kW/m^2/y was used as a U.S. average for general PV and 2500 kW/m^2/y was used for direct normal insolation in the U.S. Southwest for concentrating PV with two-axis tracking (concentrating PV requires direct sunlight just as CSP technologies do; the justification for using U.S.-average and Southwest insolation values is the same as the one for capacity factors provided in Section 3.4). The general PV packing factor for Lackner et al. [28], 2.5, was taken from two sources reporting the same factor for this technology subcategory [2,29] and fit within the range reported in a third [20].

Deficiencies in study assumptions revealed themselves through comparison of study calculations with a defined algorithm. These deficiencies were corrected where possible. One such deficiency was discovered in the PV system efficiency in DeMeo and Galdo [29], which was assumed to be 0.05. This is an extremely low efficiency for current PV systems, and is attributable to the state of technology at the date the study was published (1997). The low efficiency resulted in a rather high LUEI estimate for general PV: 27.78 (m^{2}y)/MWh. By increasing the efficiency to the minimum listed efficiency among all other PV studies (0.095 [2])—a conservative approach—the LUEI estimate was harmonized to 14.62 (m^{2}y)/MWh, which is still toward the upper end of the range for most general PV estimates, but is much more reasonable than it was prior to harmonization. The harmonized values, organized by algorithm, are presented in full in the online Supplementary materials.

4. Results and discussion

The harmonization provides a range of results explained by variability in algorithm parameters. This variability has several possible explanations.

4.1. Range of results

The initial solar LUEI estimates are displayed in Fig. 1 as they were aggregated (prior to screening or metric conversion). The estimates cover a wide range, particularly those reported in m^2/MWh, which cover 4 orders of magnitude. The estimates, post-harmonization and divided by technology subcategory, are displayed in Fig. 2. The post-harmonization results, which cover 2 orders of magnitude, show a range that is comparable to the pre-harmonization ranges of reported LUEI in m^2/MW and (m^{2}y)/MWh, but significantly less than that reported in m^2/MWh.

While this harmonization did attempt to reduce the overall variability in reported LUEI values, its primary purpose was to fully describe that range. Since almost all harmonized results are calculated using the same parameters, equalizing those parameters would reduce the range in solar LUEI estimates to zero (except for the model output ranges not incorporated into the algorithms, described in Section 3.3). The purpose of this study is not to reduce the range of results to zero (i.e., to calculate solar LUEI for a specific technology at a particular location), but rather to characterize the reasonable variability in results across the wide variety of solar technologies and applications. This characterization supports decision making by not only providing reliable, harmonized estimates of solar LUEI but also communicating the context of those estimates and the ranges they can cover given different technology and location options. The range on display in Fig. 2 is caused by variability in certain calculation parameters such as insolation (varies by location) and packing factor (varies primarily by technology).

4.2. Analysis of variability

The variability in algorithm parameters accounts for the range of results in Fig. 2. These parameters and their ranges are displayed in Table 2. No single parameter appears to vary significantly more than another, and therefore have a dominant influence on the range of solar land use energy estimates. Instead, they all share fairly equally in explaining this range. Plant lifetime is listed because it helps to explain some of the variability observable in the raw data prior to unit conversion (see Fig. 1). However, because the (m^{2}y)/MWh metric used for harmonization normalizes the LUEI estimates over plant lifetime, variability in lifetime does not contribute to the harmonized range shown in Fig. 2.

The technology and location assumptions of each study have a primary impact on these parameters. Insolation is latitude and climate dependent. Packing factor represents the spacing required for a certain technology and location. System efficiency wholly depends on the combination of electrical technologies chosen, and capacity factor depends on both technology capabilities and the amount of sunlight at a given location. However, several less obvious factors are probably affecting the parameter variability, including combinations of extreme assumptions, technological advancement, definitional ambiguity, and technology specifics below the subcategory level used in this study.

4.2.1. Extreme parameter combinations

The highest estimate for solar LUEI displayed in Fig. 2 stands out as being notably greater than the other estimates. This estimate of 55 (m^{2}y)/MWh from Graebig et al. [6] can be largely explained by the combination of two relatively extreme factors in comparison to the other studies that passed the screening process. One factor is that the plant whose LUEI was estimated is located in Germany. Thus, its insolation is estimated at 1100 kWh/m^2/y. No other insolation value gathered in this study

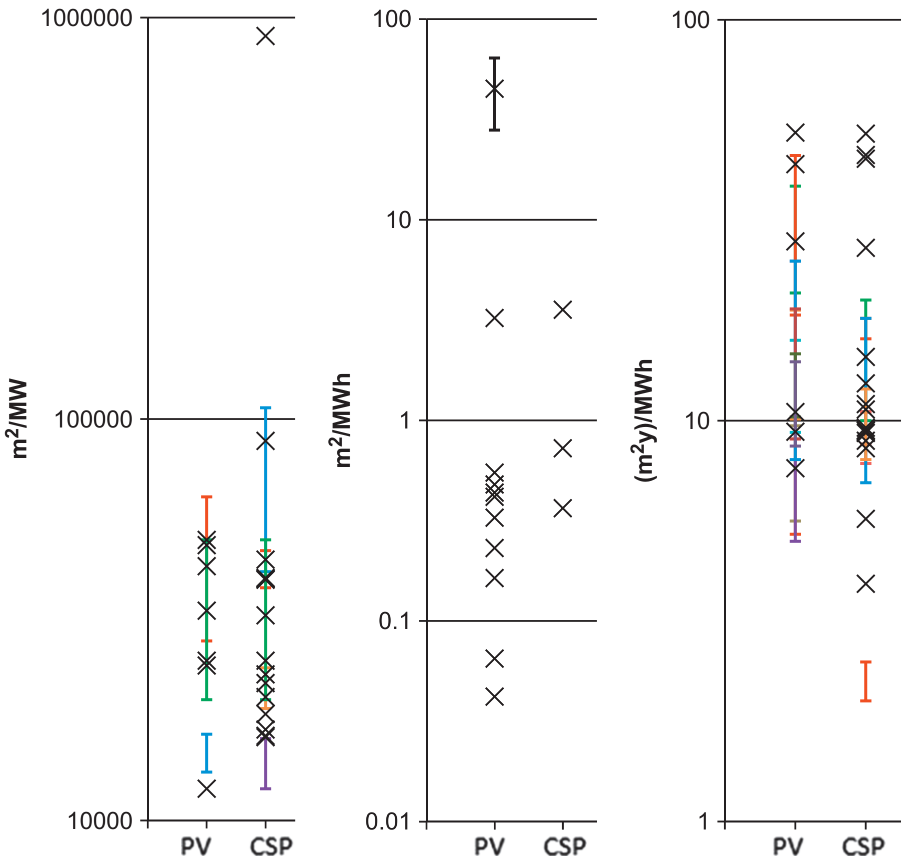

Fig. 1. (Color online) Data aggregation results: Pre-harmonization results are shown on a log scale for all three metrics of solar LUEI present in the literature. Discrete estimates are represented by X-marks, while ranged estimates are represented by lines. The lines are colored to differentiate between overlapping ranges from different studies.

was nearly as low as this. The next lowest insolation value is 1770 kWh/m^2/y [2] (although Dijkman and Benders [5] use low insolation for Scandinavian conditions, this value is not provided). The other factor is that the technology is two-axis tracking PV, which requires a great deal of spacing between modules (packing factors are as high as 5 for concentrating PV, which also tracks on two axes [2,29]). Low insolation and a high packing factor combine to create a high LUEI value. However, since this study uses data from an actual plant, these extreme parameter values are valid.

Another example is the wide range that contains the highest estimates for general PV (18.4–45.9 (m^2y)/MWh) from Dijkman and Benders [5]. The maximum value in the range is an estimate for a theoretical low-efficiency system in Scandinavian insolation conditions. These extreme parameters again combine to create an extreme but credible LUEI estimate. Although these two examples are from parts of Europe where solar conditions are far from ideal, when all non-U.S. data are excluded from the analysis the range of LUEI values is 5–46 (m^2y)/MWh, which is only slightly narrower than when all data are included, suggesting that non-ideal solar conditions are not solely responsible for the wide range in LUEI values (see Table 2).

4.2.2. Technological advancement

While most of the studies used for this project were published in the past 10 years, technological advancement—particularly in the efficiency of PV technologies—has been rapid over that time period [37]. Furthermore, several of the most useful studies cited data from more than 10 years ago. To examine the effect dated sources may have on the results, values of LUEI were plotted against their date of publication (see the online Supplementary materials). No discernible correlation between date of publication and the magnitude of the LUEI was found. While DeMeo and Galdo [29] did show evidence of an outdated efficiency value (see Section 3.5), this value was corrected in harmonization.

4.2.3. Definitional ambiguity

While probably a minor source of variability, ambiguity can cause uncertainty in some parameters. Studies can vary in how they define efficiency. All studies that list efficiencies imply that they are system efficiencies, except for DiPippo [22], which gives a cell efficiency, and Denholm and Margolis [23], which provides both a cell efficiency and a balance of system efficiency (which can be combined into an overall system efficiency). However, since efficiency is rarely explicitly defined in these studies, cell conversion efficiencies could easily be used instead of overall system efficiency without the difference being obvious. Because balance of system efficiencies are relatively high, cell efficiency and overall system efficiency are normally close enough to each other in value that they can be confused for one another; DiPippo [22] and Denholm and Margolis [23] give cell efficiencies of 0.12 and 0.135, respectively, which both fall well within the range of system efficiencies in the harmonization (0.095–0.202). This closeness in value also means that if one efficiency parameter were mistaken for another, the impact on the LUEI estimate would probably not be large.

Plant area and packing factor can also be ambiguous parameters. Many studies clearly communicate what is counted in the

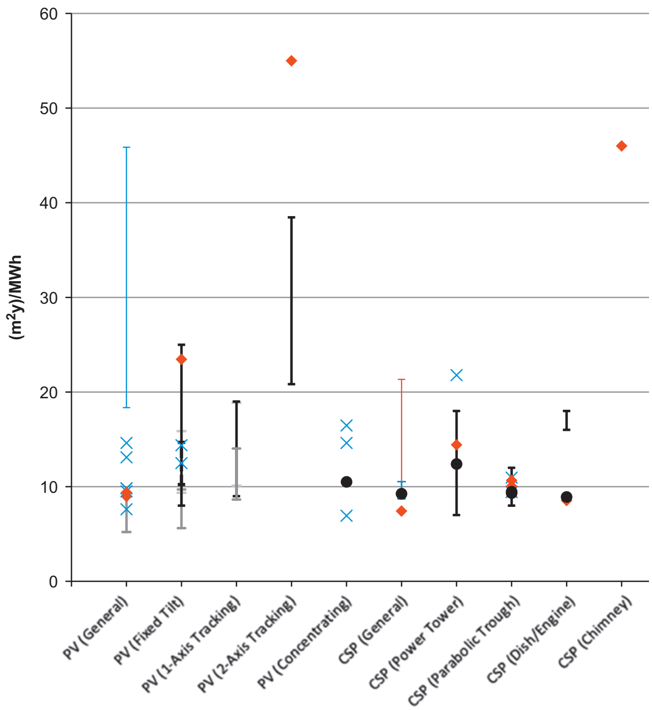

Fig. 2. (Color online) Harmonized results: The harmonized results of this study, normalized over plant lifetime and separated into technology subcategories, are shown. Points (X-marks, diamonds, and circles) represent discrete values, and lines represent ranges. Blue lines and X-marks represent estimates using the insolation method. Red lines and diamonds represent estimates using the area-output method. Grayscale lines and circles represent estimates from models where neither algorithm could be assigned. Differences in grayscale differentiate between overlapping ranges.

Table 2
Variability within algorithm parameters.

Parameter	Min	Max	Percent difference
Insolation (kWh/m^2/y)	1100	3011	63%
Packing factor	1.5	5	70%
System efficiency	0.095	0.202	53%
Capacity factor	0.12	0.49[a]	76%
Plant lifetime	25	60	58%
LUEI	**5**	**55**	**91%**

These are the overall range of study inputs for each key algorithm parameter, plus plant lifetime. Percent difference is calculated by dividing the range by its maximum.

[a] CSP parabolic trough system with onsite thermal storage.

plant area, either by stating what is included in the packing factor [2] or by using actual plant fence line areas [6,24,25]. However, not all studies are this clear. Trieb et al. [30] provides data labeled "land use for solar collector," which could include or not include land for spacing, roads, and balance-of-system facilities (for power electronics and—in the case of power towers or parabolic troughs—coolant loops and electricity generation equipment). DeMeo and Galdo [29] provide an equally ambiguous label of "land requirements" for their data. Stoddard et al. [32] give total land available in a region coupled with generation potential, but do not specify whether that generation potential incorporates balance-of-system area or just panels and spacing. Since only one of these six studies provides solar LUEI estimates notably different from the others—Graebig et al. [6], which gives intensities of 23.46 and 55 (m^{2}y)/MWh—it seems unlikely that such potential definitional differences have a large effect on solar LUEI estimation. Nevertheless, uncertainty in these estimates could be reduced if all studies were unambiguous in their parameter definitions.

4.2.4. Technology specifics

Differences in technology assumptions are recognized by separating the harmonization results by technology subcategory in Fig. 2. However, these subcategories still cannot fully reflect differences among technologies. By grouping results together, some specific differences in technological applications are obscured. For example, Denholm and Margolis [23] account not just for fixed-tilt PV arrays, but also for such arrays at different angles—flat, 10°, and 25°—with differing results: 5.2–9.0 (m^{2}y)/MWh, 5.6–9.7 (m^{2}y)/MWh, and 9.4–15.9 (m^{2}y)/MWh, respectively. However, as this is the only study reviewed that has a tilt angle analysis, the technology categories were not further subcategorized to account for array angle. For most of the technology subcategories, only a few data sources exist (often there is only one for any individual calculation method), making meaningful comparisons between most subcategories difficult.

The presence of on-site energy storage is another technology factor that could introduce variability into the solar LUEI estimates. CSP plants with thermal energy storage require more land area relative to their power capacities than plants without storage because they need more solar collectors (to collect energy for both storage and immediate electricity generation) [26]. However, they also have larger capacity factors than plants without storage [26]. Since larger capacity factors result in greater energy output, but more solar collectors means more land being occupied, the effect that energy storage has on LEUI is not immediately clear. Three harmonized studies included CSP technologies with thermal energy storage. Burkhardt et al. [24] and Stoddard et al. [32] analyzed parabolic trough systems. Stoddard et al. [32] also included a power tower system. Jacobson [26] included high and low LUEI estimates for CSP with storage, but did not specify the type of CSP system. The range of LUEI estimates from these studies for CSP systems with storage [9.25–13.41 (m^{2}y)/MWh] falls within the lower part of the overall LUEI range for CSP technologies in this study. However, since these estimates for CSP with storage fall well within the range of LUEI for CSP technologies without storage, and because there are only a small number of estimates (6 estimates from 3 sources), this study cannot identify a significant difference between LUEI for CSP with storage and CSP without storage. Storage does not appear to play a major role in the overall variability in LUEI in this study, but due to the paucity of data nothing conclusive about its actual impact on LUEI can be determined.

This study subcategorizes PV technology by degree of tracking because that is how PV technologies were classified in many of the harmonized studies. However, other differences in PV technology have the potential for introducing variability into LUEI estimates. For example, different PV cell technologies (e.g., monocrystalline, polycrystalline, and thin film) convert sunlight into electrical energy at different efficiencies [37], resulting in different required cell areas for the same amount of electricity production. Unfortunately, none of the harmonized studies differentiated between PV technologies in this way, so this possible source of variability in LUEI estimates could not be examined.

Unlike cell technologies, degrees of tracking were differentiated in this study, and at least one category (two-axis tracking) appears to have a significantly higher solar LUEI than the others. This relationship is supported by Denholm and Margolis [23], who explain that while two-axis tracking significantly improves cell efficiency, the substantial increase in spacing required between modules to avoid shading more than makes up for the increased power production, resulting in a higher LUEI. However, the two estimates of LUEI for two-axis tracking present in the

harmonization are not enough to definitively demonstrate that two-axis trackers use land less efficiently, especially since one of those estimates [6] has other clear factors contributing to its high LUEI (it is the extreme example from Graebig et al. [6] discussed in Section 4.2.1).

5. Conclusions

A harmonization process can result in the determination of a single "best" estimate [1]. This study does not take that step because the solar land use intensity question has many correct answers, depending primarily on choice of technology and geographic location. Instead, this study provides a robust depiction of the inherent variability in solar LUEI estimates across the industry—reducing the uncertainty in this value from 4 orders of magnitude to 2 [5–55 (m^2y)/MWh].

This robust depiction of variability was accomplished by screening existing sources for comparable data, defining a common metric of comparison and converting screened data to that metric, harmonizing and displaying estimates of solar LUEI across technologies, and defining two meta-model algorithms for calculating LUEI [Eqs. (1) and (2)–(4)]. These algorithms not only aided in harmonization, but also provide a standard method for future solar LUEI calculations. This standardization may guide future study in this area so that it will be comprehensive and comparable to other studies. Moreover, this harmonization revealed large gaps in lifecycle analysis of solar land use. Land used for manufacturing and disposal of solar energy technologies needs further study and characterization, and the algorithms developed in this study provide a foundation for moving forward.

The characterization of variability and standardization of calculation algorithms that are the thrust of this study can reduce confusion and provide reliable information about solar energy land use to stakeholders and decision makers. Reducing uncertainty with respect to projected environmental impacts of solar energy development can streamline project review and approval timelines, lower the risk of project failure, and, ultimately, translate into reduced costs. Specifically, by defining standard algorithms for calculating the amount of land solar projects used, and by establishing robust land use values supported by a wide range of scholarly literature, the regulatory burdens associated with siting and environmental impacts can be reduced.

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Appendix A. Supplementary materials

Supplementary materials associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2013.01.014.

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